Marshal Space Flight Center Fluids Workshop

Turbine Aerodynamics

Design Tool Development

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Riverbend Design

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Turbine Aerodynamic Design Tool Development*

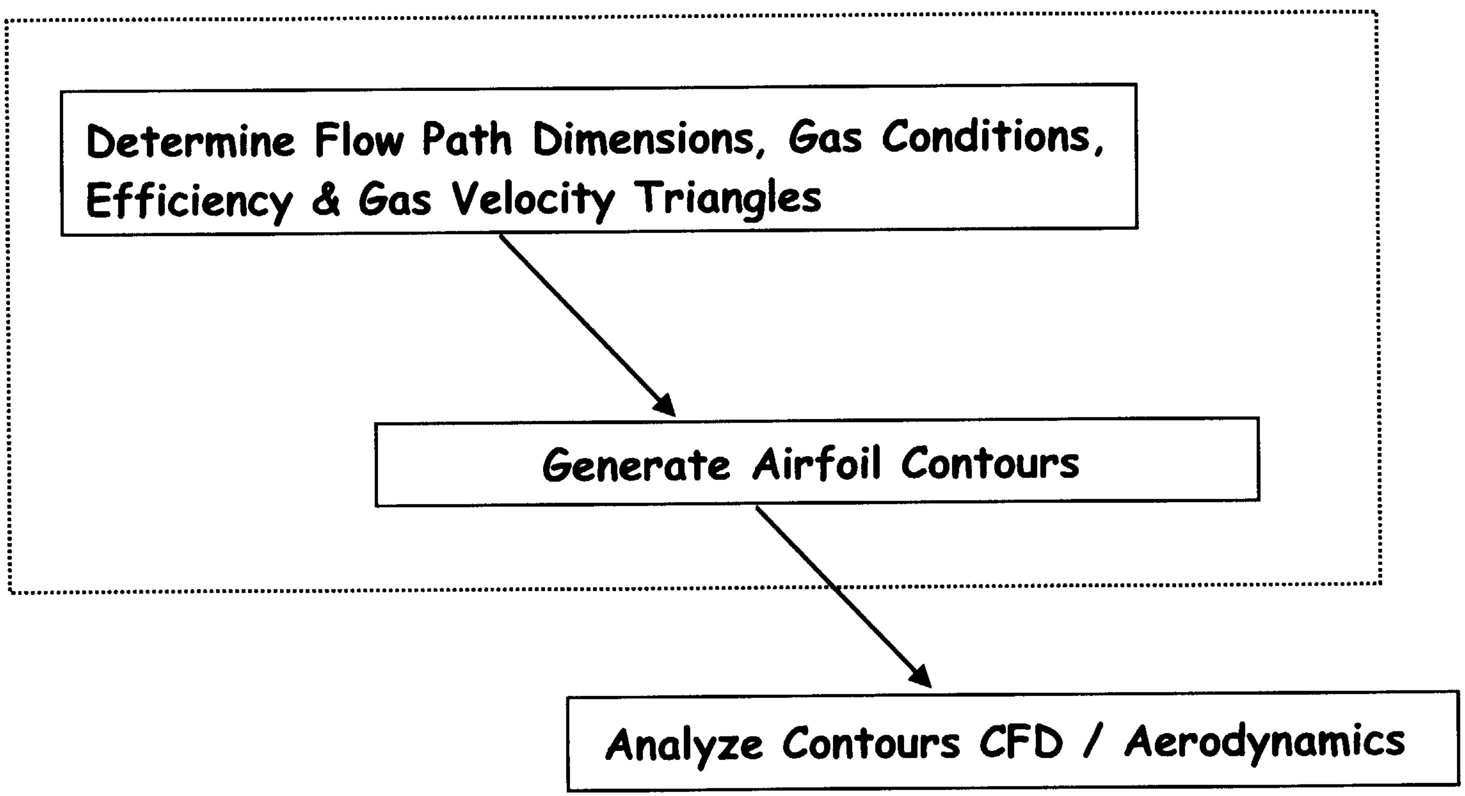
Presentation Outline

- Meanline Design / Off-design Analysis
- Airfoil Contour Generation & Analysis

* Effort funded by MSFC

Turbine Aerodynamic Design Tool Development

Design Process Outline



Turbine Aerodynamic Design Tool Development

Meanline Code Development and Enhancement

Objective

Develop software to run rapid meanline analyses

- Design Maps
- Off-design Calculations and Maps

Requirements

Applicable to rocket turbines

- High work coefficient / Supersonic
- Multi stage / spool

Turbine Aerodynamic Design Tool Development

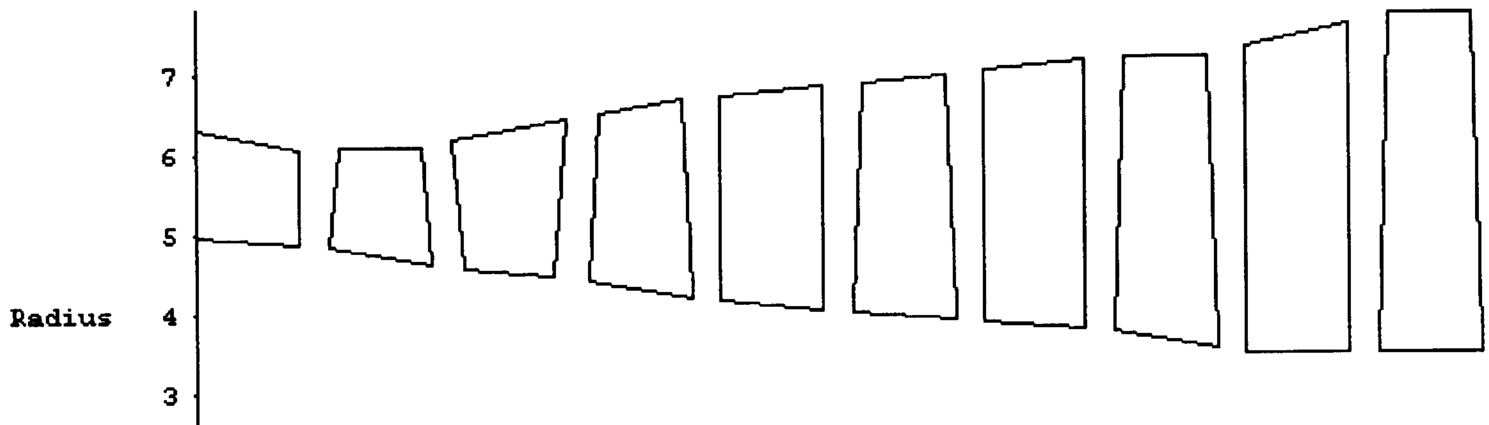
Meanline Description - MLFP

General Capabilities

- Read / write input & write output files
- Flow path generation
- Performance prediction
- Parametric Design Map Generation
- Calculate gas conditions / velocity triangles
- Write input file for off-design code
- Displays
  - Numerical output
  - Flow path elevation

Turbine Aerodynamic Design Tool Development

Flow Path Generation Approach



Input Parameters

- 1st stage rim diameter
- Last stage annulus area
- ID flow path angle for each foil
- Blade height for each stage (% last stg blade)
- Axial chords and spacing (% axial chord)
- Shrouded or unshrouded blades

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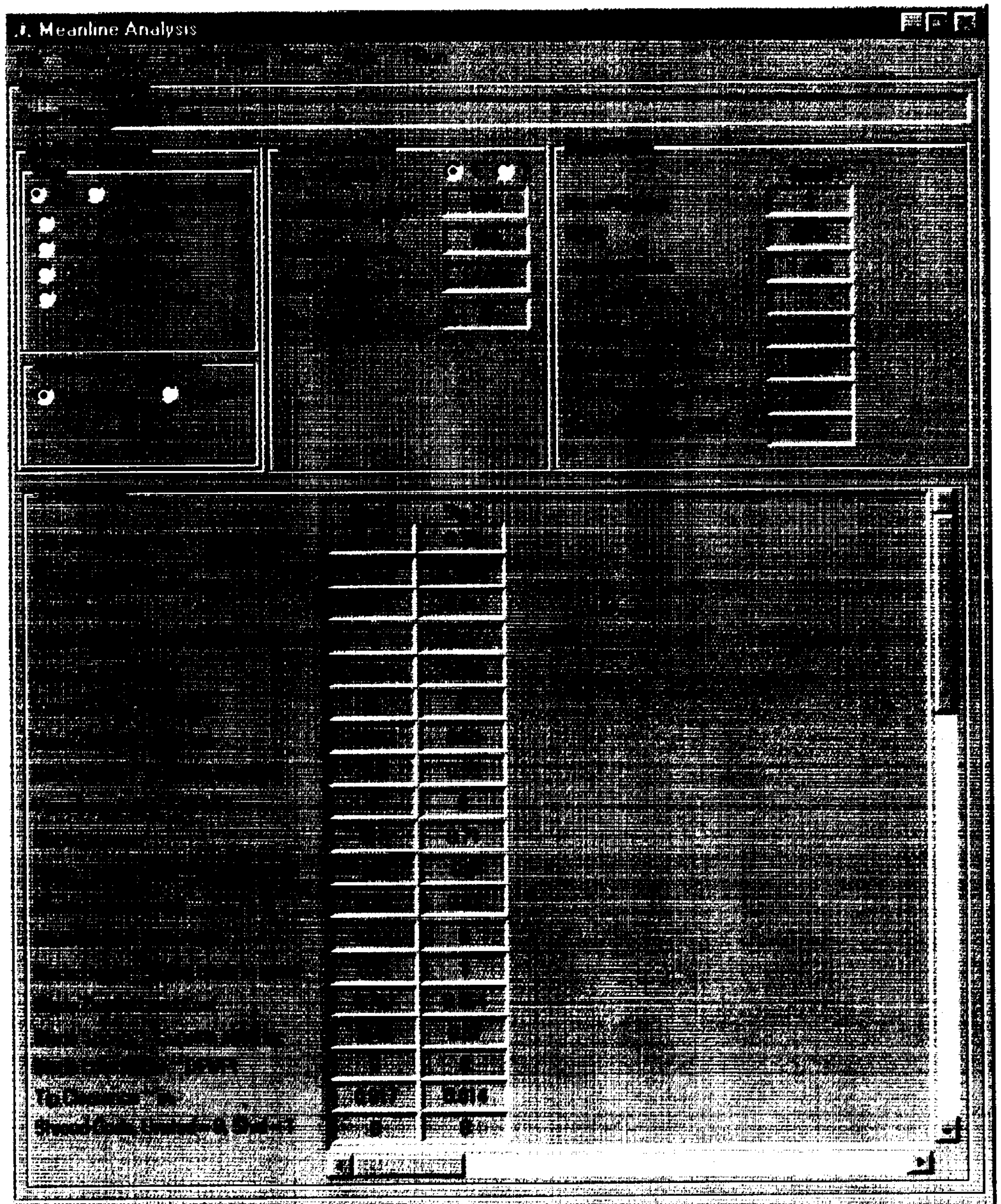
MLFP Description ~ Input Screen



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MLFP Description ~ Sample Numerical Output Screens

Meanline Output ~ SSME Test

SaveAs Copy Print

SSME Test

SPOOL SUMMARY

	Spool 1			
Efficiency	0.8543	t-t	0.8149	t-s
P/P	1.4631	t-t	1.4919	t-s
U/C isen.	0.4779	t-t	0.4667	t-s
U/C actual	0.5170	t-t		
W*sqr(T*R)/P	24.021	inlet	33.562	exit
Work	11.62	btu/lbm		
Power ~ Total	162.9	btu/s	230.4	hp
Power ~ Shaft	162.91	btu/s		
Torq	173.4	ft-lbs		

STAGE SUMMARY

	Stage 1			
Efficiency	0.8433	t-t	0.7365	t-s
P/P	1.2348	t-t	1.2745	t-s
U/C isen.	0.4462	t-t	0.4170	t-s
U/C actual	0.4858	t-t		
Cx/Um	0.596	bld in	0.618	bld ex
Reaction	0.467	Ps	0.485	Ts
Work	6.51	btu/lbm		
Power ~ Tot.	91.3	btu/s	129.1	hp
Power ~ Shaft	91.3	btu/s	129.1	hp
RPM	6982.0			
AN^2 E-8	13.3			

	Stage 2			
Efficiency	0.8604	t-t	0.7738	t-s
P/P	1.1848	t-t	1.2082	t-s
U/C isen.	0.5141	t-t	0.4875	t-s
U/C actual	0.5542	t-t		
Cx/Um	0.623	bld in	0.635	bld ex
Reaction	0.398	Ps	0.428	Ts
Work	5.11	btu/lbm		
Power ~ Tot.	71.6	btu/s	101.3	hp
Power ~ Shaft	71.6	btu/s	101.3	hp
RPM	6982.0			
AN^2 E-8	14.8			

Meanline Output ~ SSME Test

SaveAs Copy Print

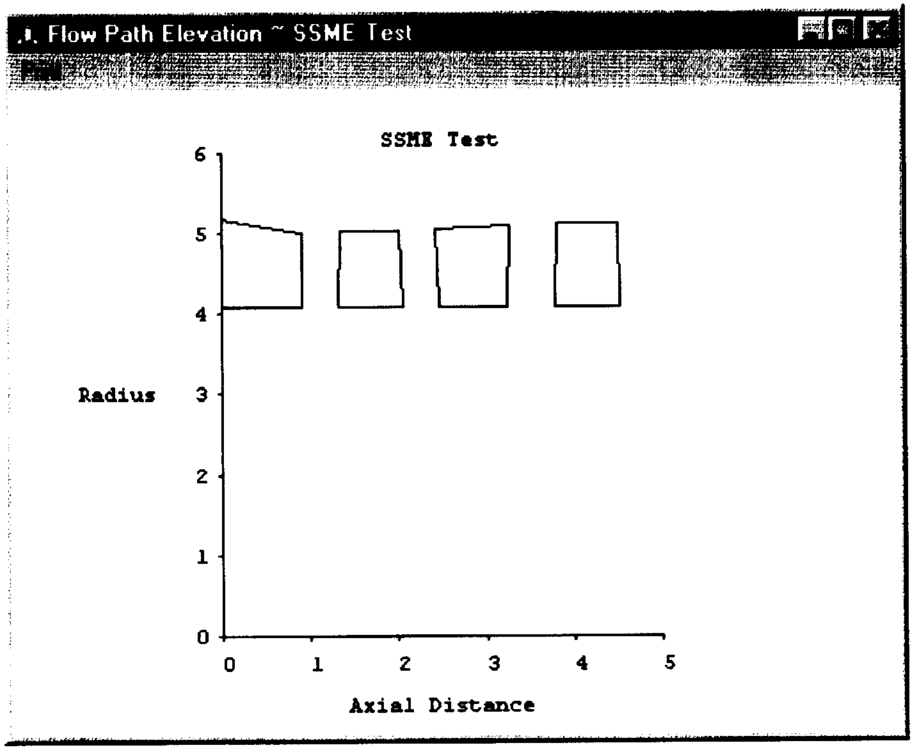
AIRFOIL ROW SUMMARY Stage 1

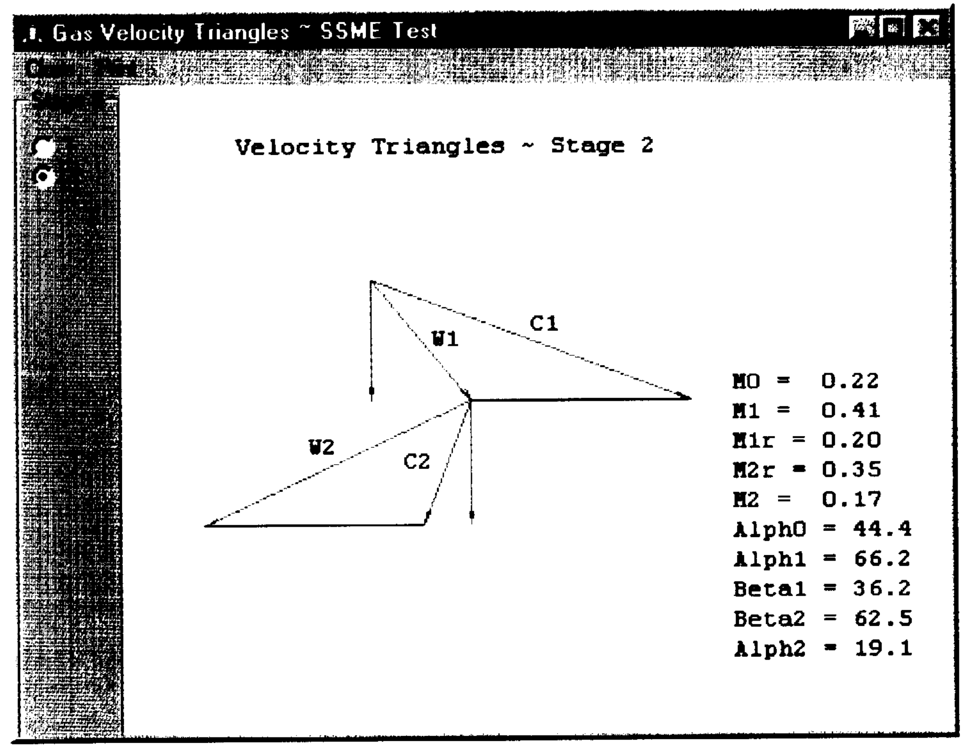
	Stator (abs)		Rotor (rel)		Stage
	Inlet	Exit	Inlet	Exit	Exit (abs)
MN	0.114	0.415	0.203	0.441	0.213
Gas Angle	0.00	68.64	43.83	69.57	46.82
Pstatic	99.1	88.1	88.2	78.5	78.5
Ptotal	100.0	99.2	90.8	89.7	81.0
Tstatic	548.6	531.6	531.9	516.2	518.1
Ttotal	550.0	550.0	536.3	536.3	522.9
Tot. Vel.	130.4	469.7	229.1	490.9	237.9
Tang. Vel.	0.0	437.4	158.7	460.0	173.4
Axial Vel.	130.4	171.1	165.3	171.4	162.8
Umean			277.4	277.4	
Root rad.	4.076	4.076	4.076	4.076	
Mean rad.	4.622	4.539	4.553	4.553	
Tip rad.	5.169	5.001	5.030	5.030	
Ann. Area	31.73	26.38	27.28	27.28	
Flow	14.02	14.02	14.02	13.32	14.02
gama	1.400	1.400		1.400	
Cp	0.240	0.240		0.240	
Rgas	53.35	53.35		53.35	

ROW OVERALL	Stator (abs)	Rotor (rel)
Psin/Psx	1.125	1.125
Turning	68.64	113.40
CR	3.302	2.066
Re based on bx	1303813.	978753.
Dvisc	0.00001228	
No. Airfoils	52	47
TE Aeff	9.609	9.524
Gage Aeff	9.554	9.445
Gage Aann	27.45	27.28
Gage Angle	69.632	69.745
Gage Flow	14.02	13.32
Gage Pt	99.78	90.41
Gage Tt	550.0	536.3

Turbine Aerodynamic Design Tool Development

MLFP Description ~ Elevation & Velocity Triangle Output Screens





Turbine Aerodynamic Design Tool Development

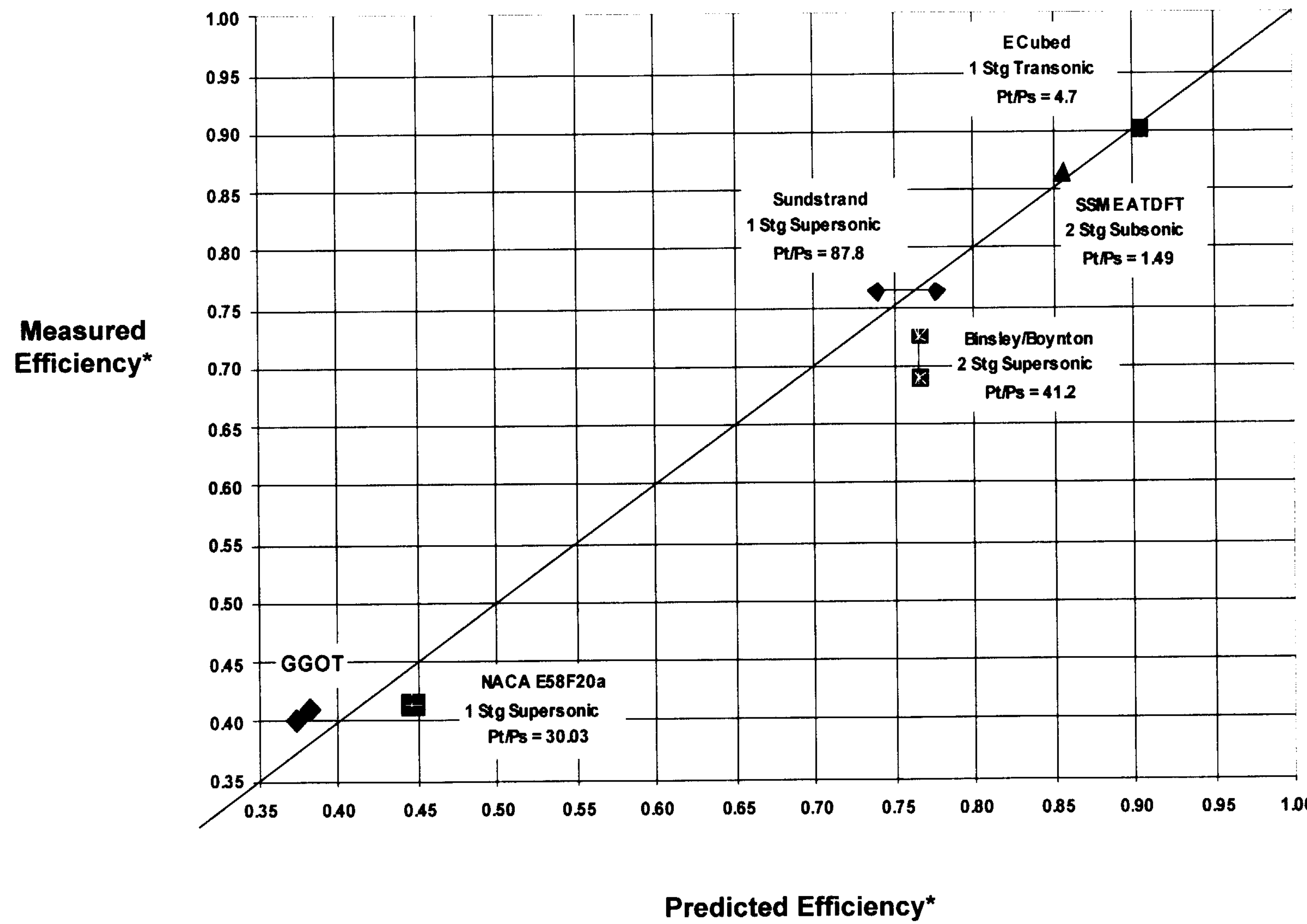
MLFP Description - Performance Prediction System

Loss correlations included

- Profile
  - AMDC (Modified by Kacker, Okapuu,)(Modified at high swirl angles)
- Reynolds #
  - AMDC
- Trailing edge blockage
  - NASA TN D-6637 (Extrap. to high blockage)
- Secondary Endwall
  - Sharma/Butler 1987 (Modified)
- Trailing edge shock
  - AMDC/E^3 (Extrap. to higher MN)
- Leading edge shock
  - Freeman/Cumpsty (Fan correlation)
- Unshrouded blade tip leakage
  - Soderberg type correlation (f{clear flow area / blade flow area})

Turbine Aerodynamic Design Tool Development

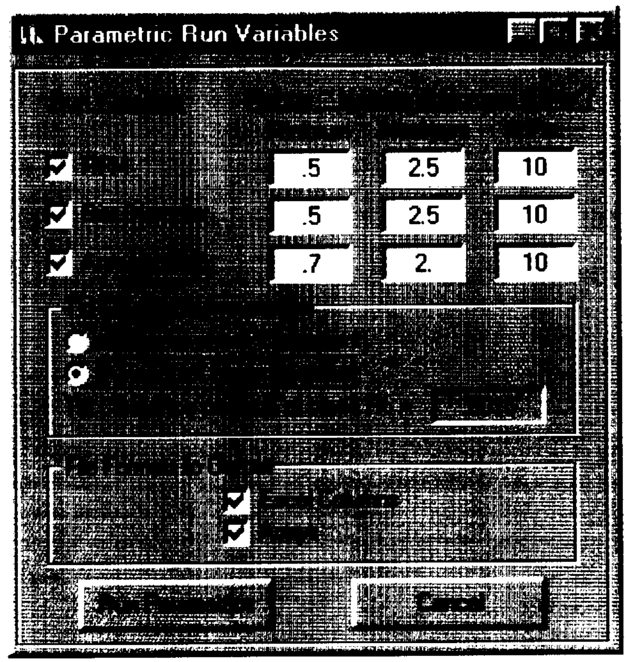
MLFP Prediction System Calibration Status



* E3 & ATD efficiencies are t-t, others are t-s

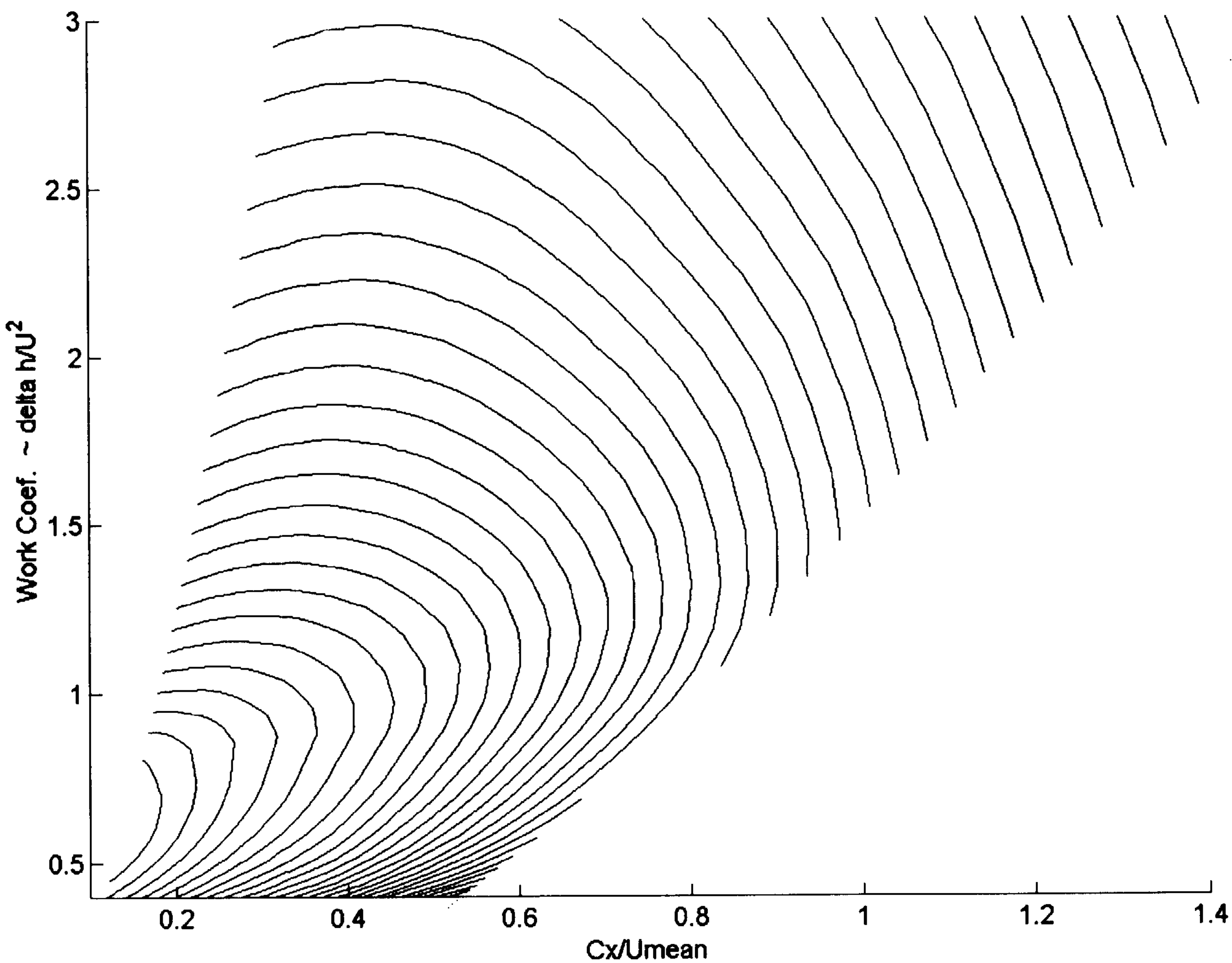
Turbine Aerodynamic Design Tool Development

MLFP Parametric Run Capability - Design Map Generation



Turbine Aerodynamic Design Tool Development

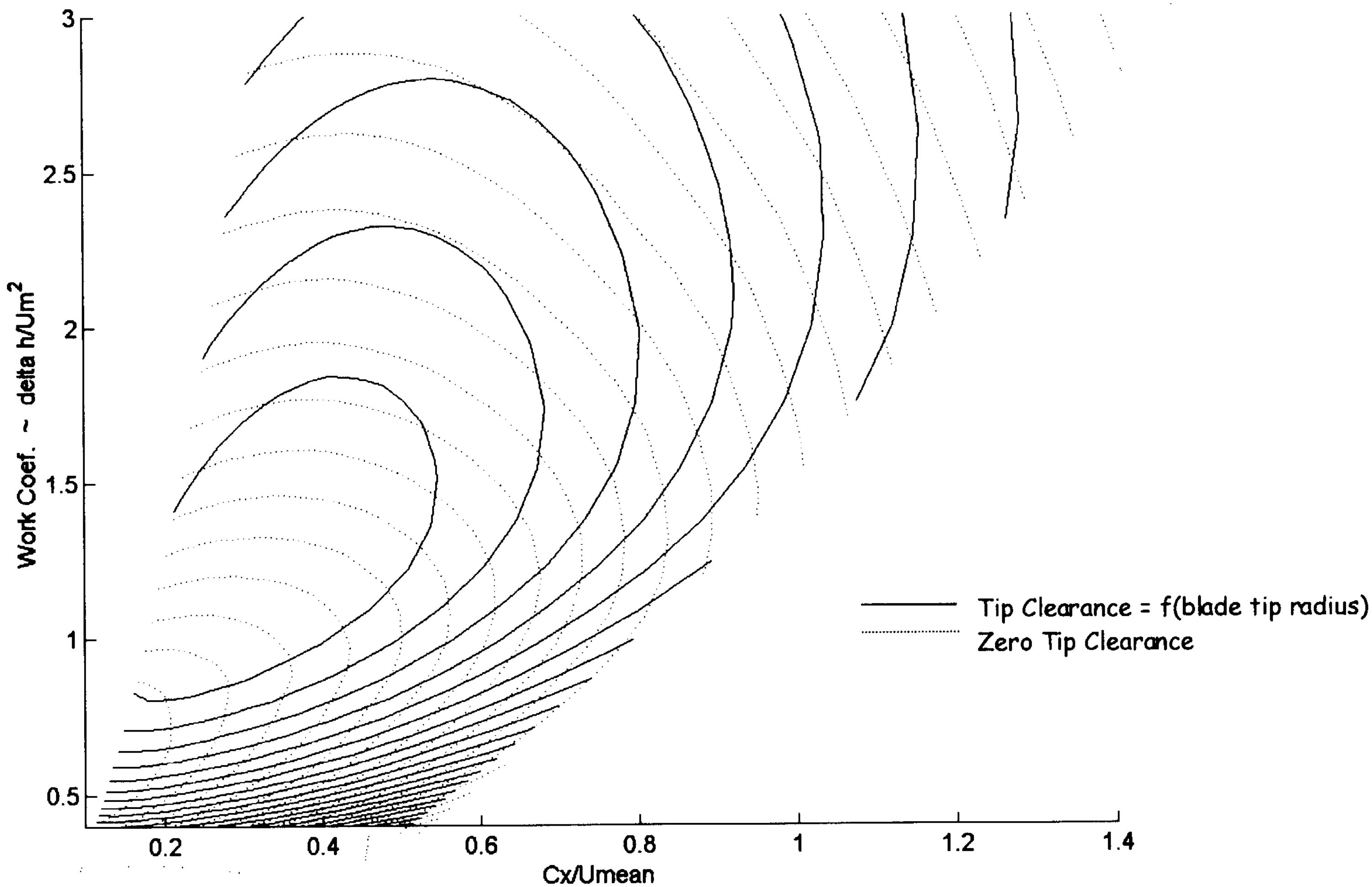
MLFP Parametric Run Capability - Classic "Smith Chart"



Zero Tip Clearance & Diameter/Aann Variation

Turbine Aerodynamic Design Tool Development

Effect of tip clearance variation on Smith Chart*



* Diameter / Aann Variation

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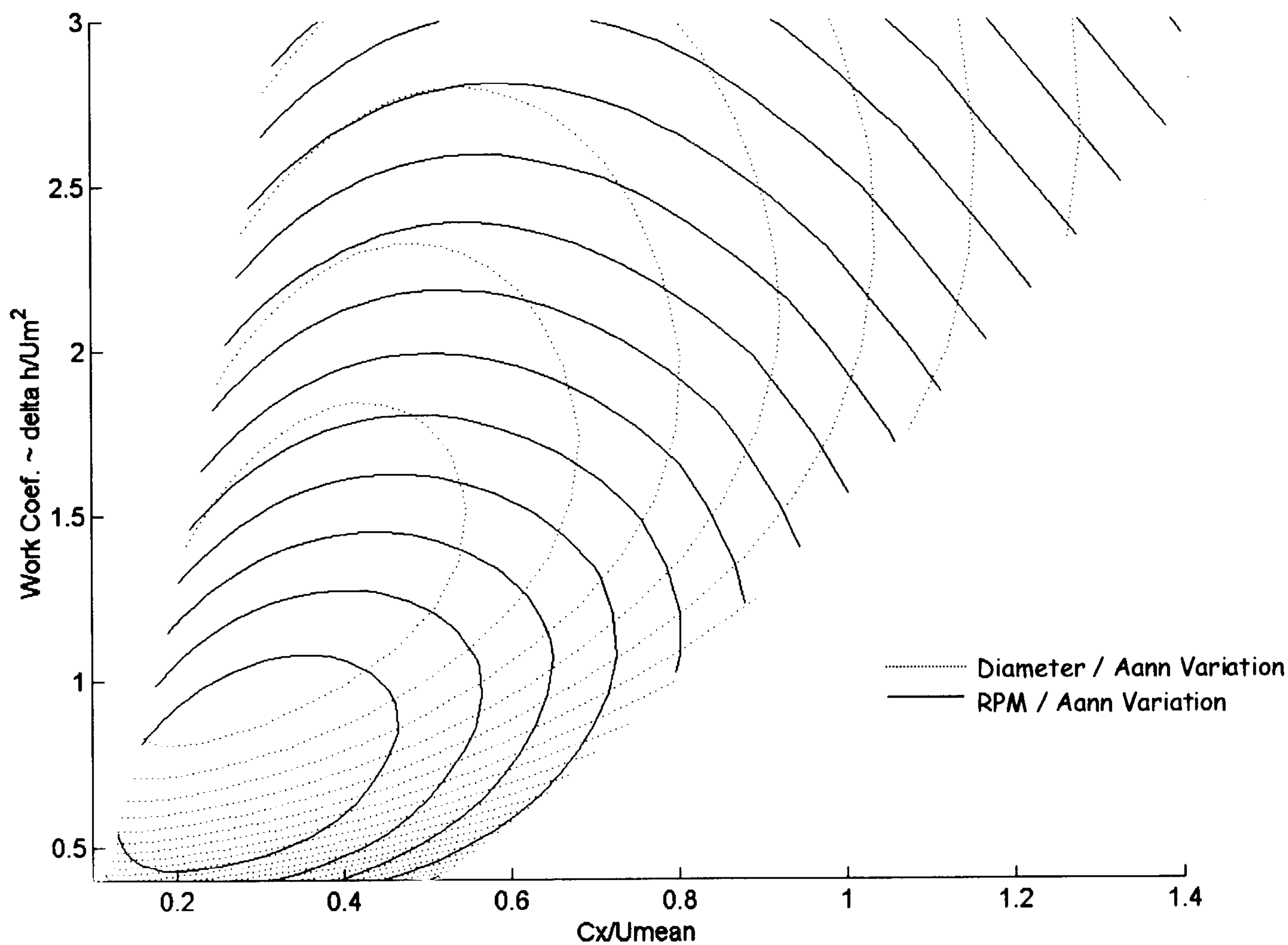
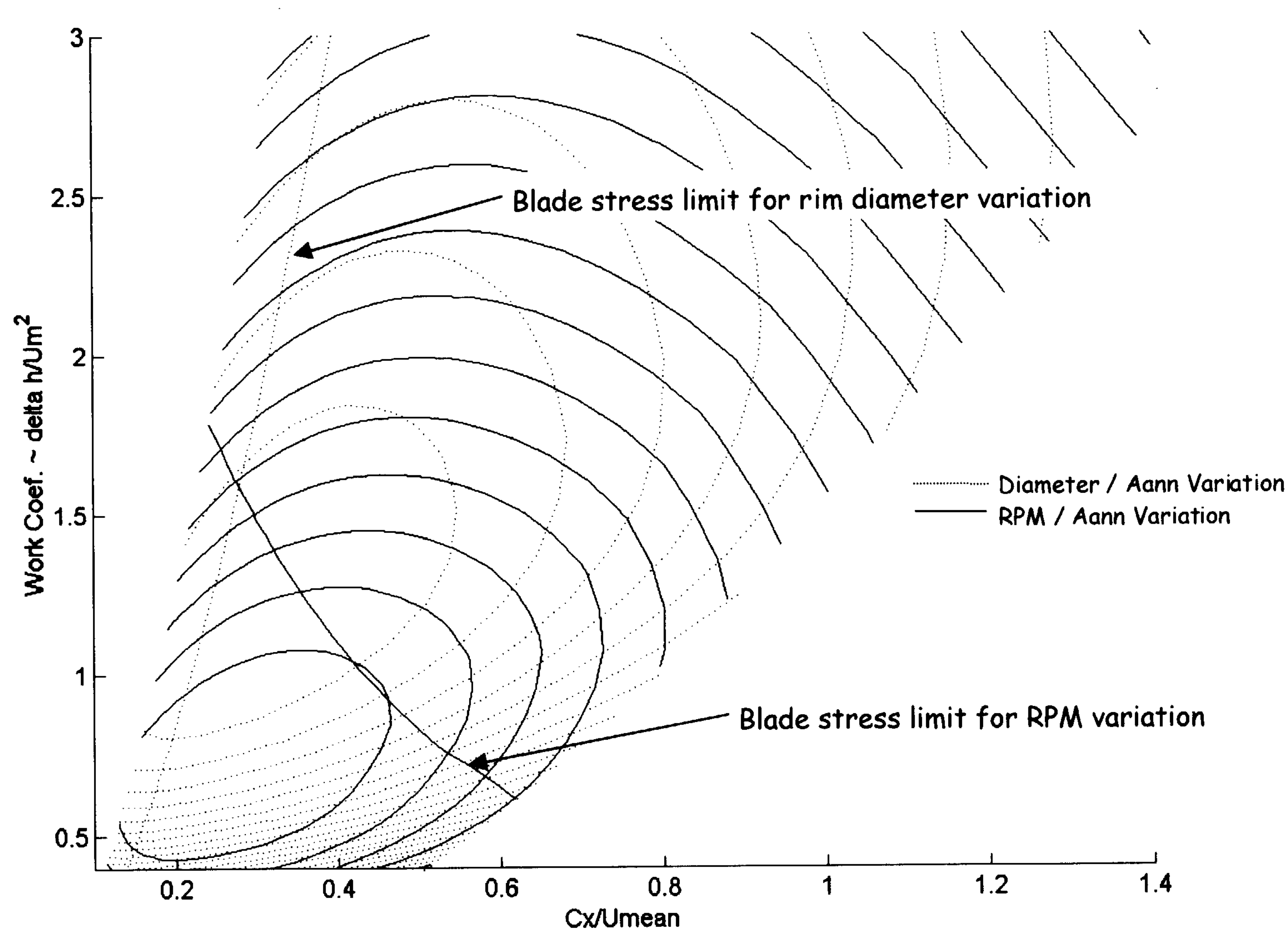
Effect of design parameter selection on Smith Chart*



* Tip Clearance = f(blade tip radius)

Turbine Aerodynamic Design Tool Development

MLFP Parametric Run Capability - Blade Stress Limitations



Turbine Aerodynamic Design Tool Development

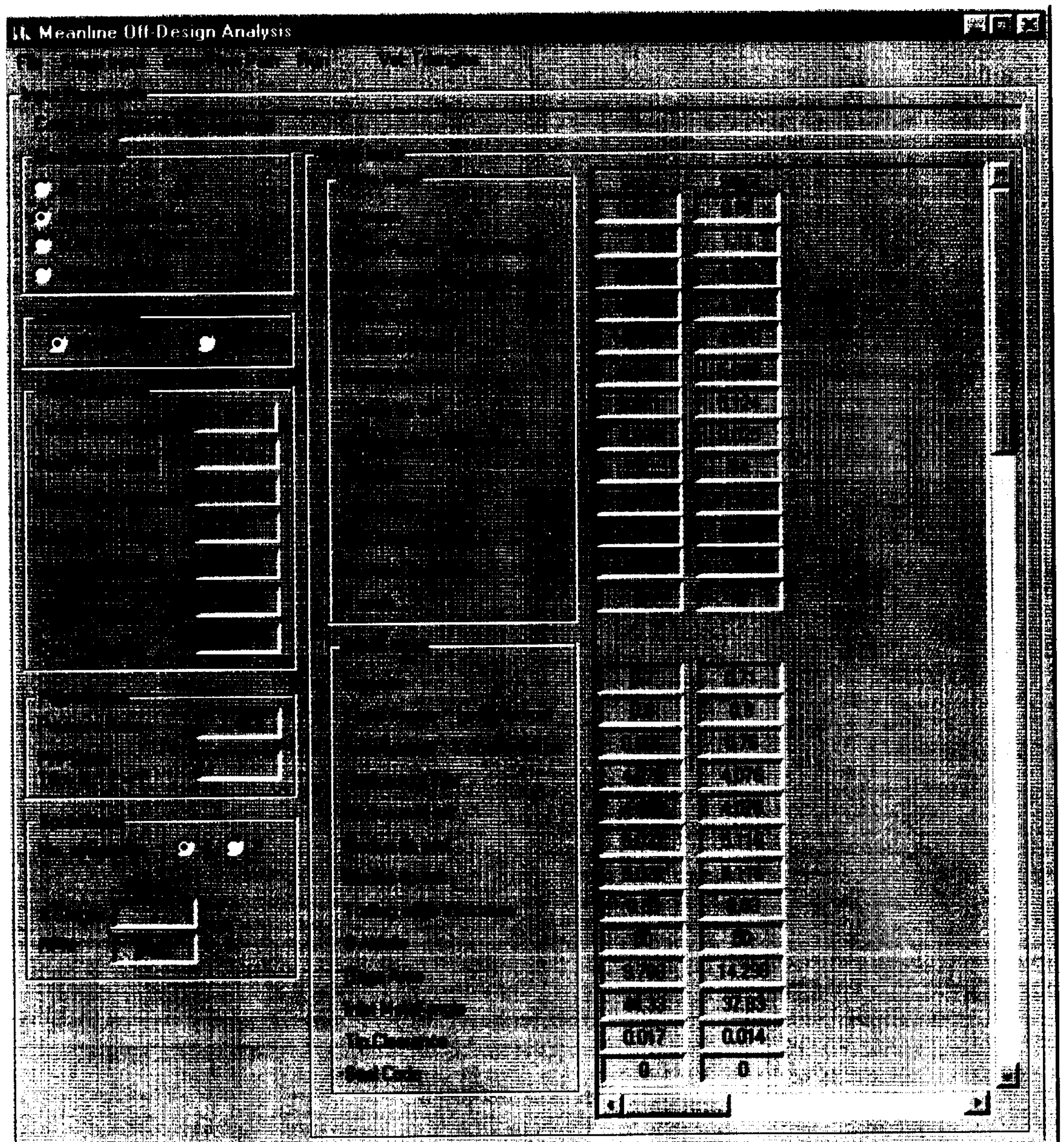
MLOD (Off - Design) Description

General Capabilities

- Read / write input & write output files
- Performance prediction
- Calculates gas conditions / velocity triangles
- Displays
  - Numerical output
  - Flow path elevation
  - Velocity Triangles

Turbine Aerodynamic Design Tool Development

MLOD (Off - Design) Description ~ Input Screen



Turbine Aerodynamic Design Tool Development

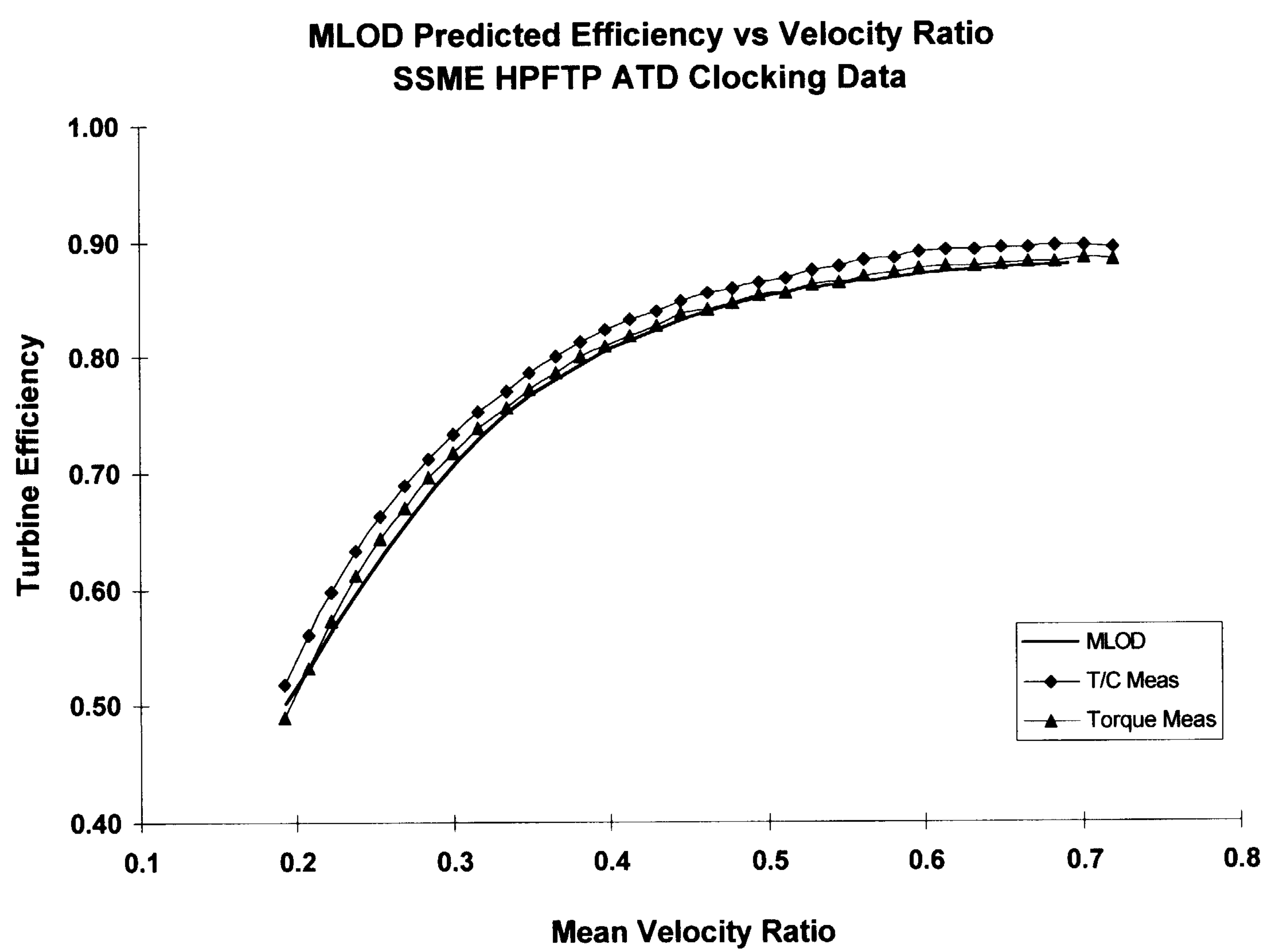
MLOD (Off-Design) - Performance Prediction System

Loss correlations included

- Profile
  - AMDC (Modified by Kacker, Okapuu,)(Modified at high swirl angles)
- Reynolds #
  - AMDC
- Incidence - profile loss
  - MK^2 ASME 89-GT-284 (Modified)
- Trailing edge blockage
  - NASA TN D-6637 (Extrap. to high blockage)
- Trailing edge shock
  - AMDC/E^3 (Extrap. to higher MN)
- Secondary endwall
  - Sharma/Butler 1987 (Modified)
- Incidence correction for secondary loss
  - MK^2 ASME 89-GT-284 (Modified)
- Leading edge shock
  - Freeman/Cumpsty (Fan correlation)
- Unshrouded blade tip leakage

Turbine Aerodynamic Design Tool Development

Off-Design Prediction System Calibration Status



Turbine Aerodynamic Design Tool Development

Meanline Design / Off-Design Summary

Current Status

Preliminary versions operational at MSFC

- Design with flow path generator (MLFP)
- Off-Design (MLOD)

Future Efforts

- Additional performance calibration
- Gas property verification
- Loss System refinement
- Off-Design Map Generation

Turbine Aerodynamic Design Tool Development

Airfoil Contour Generation and Analysis

Objective

Develop software to generate and analyze turbine airfoil contours

Requirements

Applicable to rocket turbine airfoils

- **Impulse & reaction blading**
- **Stators & turbine exit guide vanes**
- **High turning / supersonic**

Turbine Aerodynamic Design Tool Development

Airfoil Contour Generator Description

General Capabilities

Read / write input & write output files

Draw turbine airfoil contours

Calculate cross-sectional properties

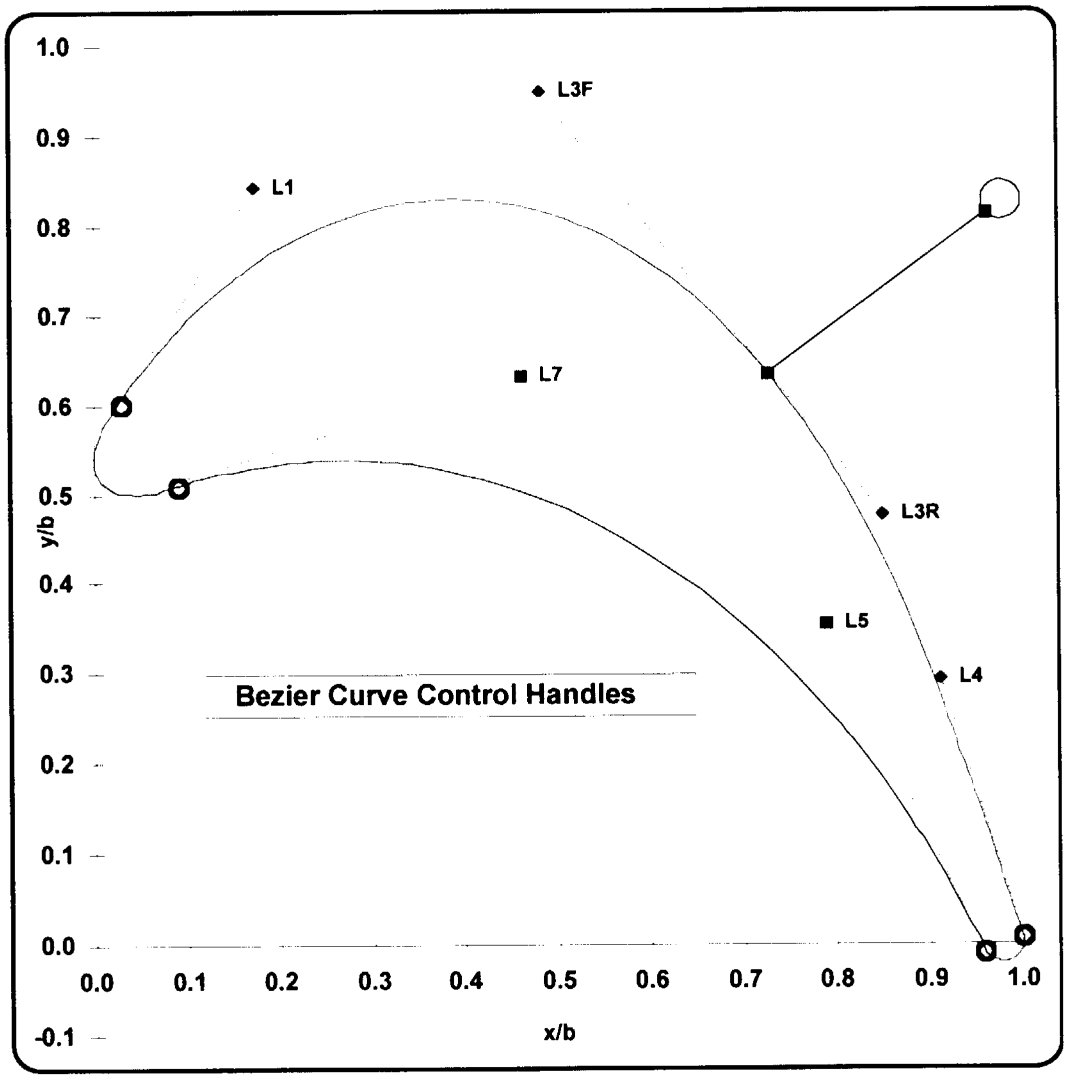
Calculate basic gas bending stresses

Write input files for 2D CFD analysis (Wildcat)

Initiate CFD run and retrieve / plot airfoil Ps distribution

Turbine Aerodynamic Design Tool Development

Airfoil Contour Generation Approach



Turbine Aerodynamic Design Tool Development

Airfoil Generator Interface

Case Name: SSME 1B

File Name:

Draw Contour/Rc/Ag | Run WildCat | Save Input & Output

Airfoil Input

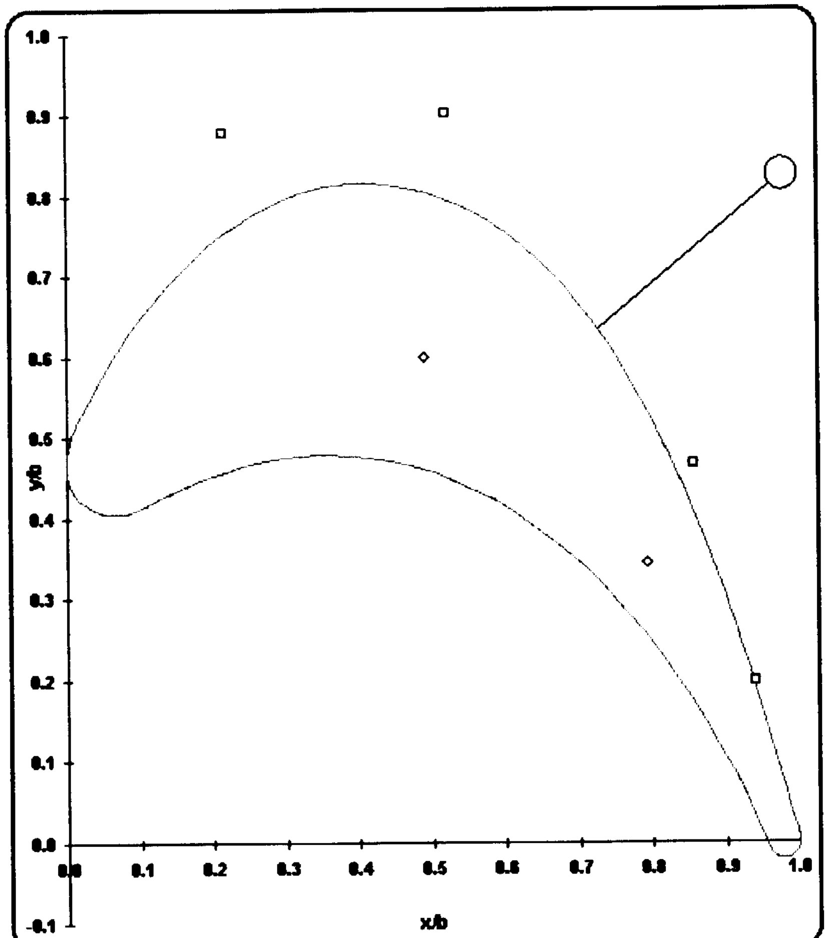
No. of Airfoils	50
Axial Chord	0.7000
Section Radius	4.6025
H/L	0.4050
Gage Angle	69.0861
LED	0.11000
LE ellipse ratio	1.5000
Beta 1	44.0000
LE Wedge Ang	35.000
LEW Fraction	0.4800
TED	0.0300
Beta 2	68.940
TE Wedge Ang	8.100
TEW Fraction	0.5000

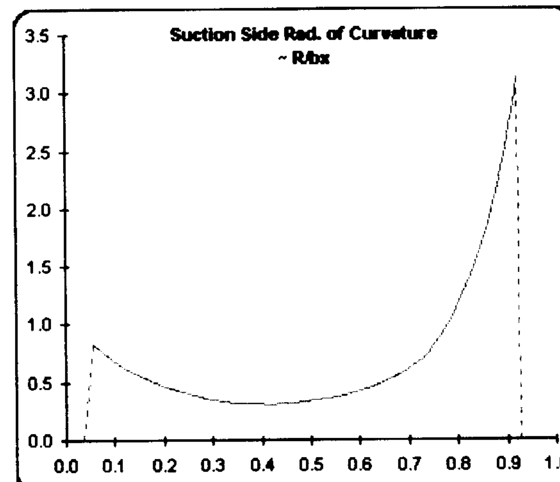
Geometry Handles

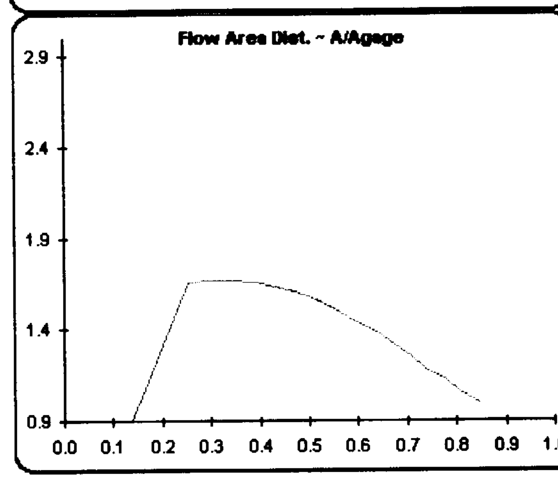
Uncovered Turn	20.6196
L1/bx	0.4100
L3F/bx	0.3400
L3R/bx	0.2100
L4/bx	0.2000
L5/bx	0.3900
L7/bx	0.4200

Aero Input

M1	0.2000
M2isentropic	0.4400
Tt inlet	500.000
Pt inlet	100.000
Hle/H1	1.000
Hte/Hle	1.000
H2/Hte	1.000
Beta 1 gas	44.000
Beta 2 gas	68.940
Rgas	53.350
gama	1.4000



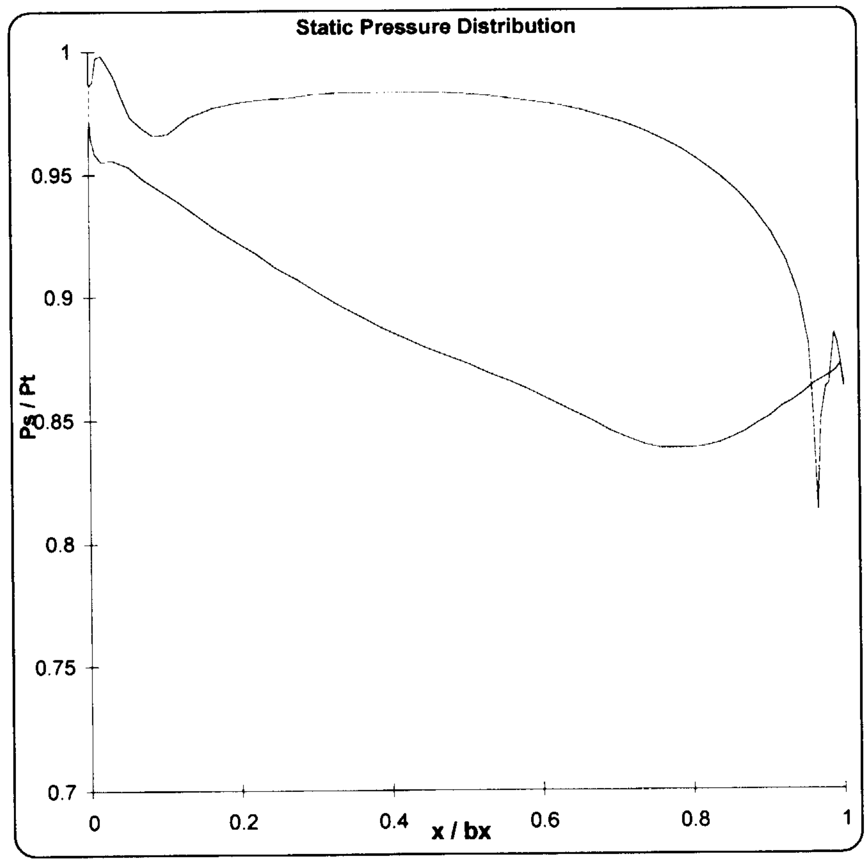




Input

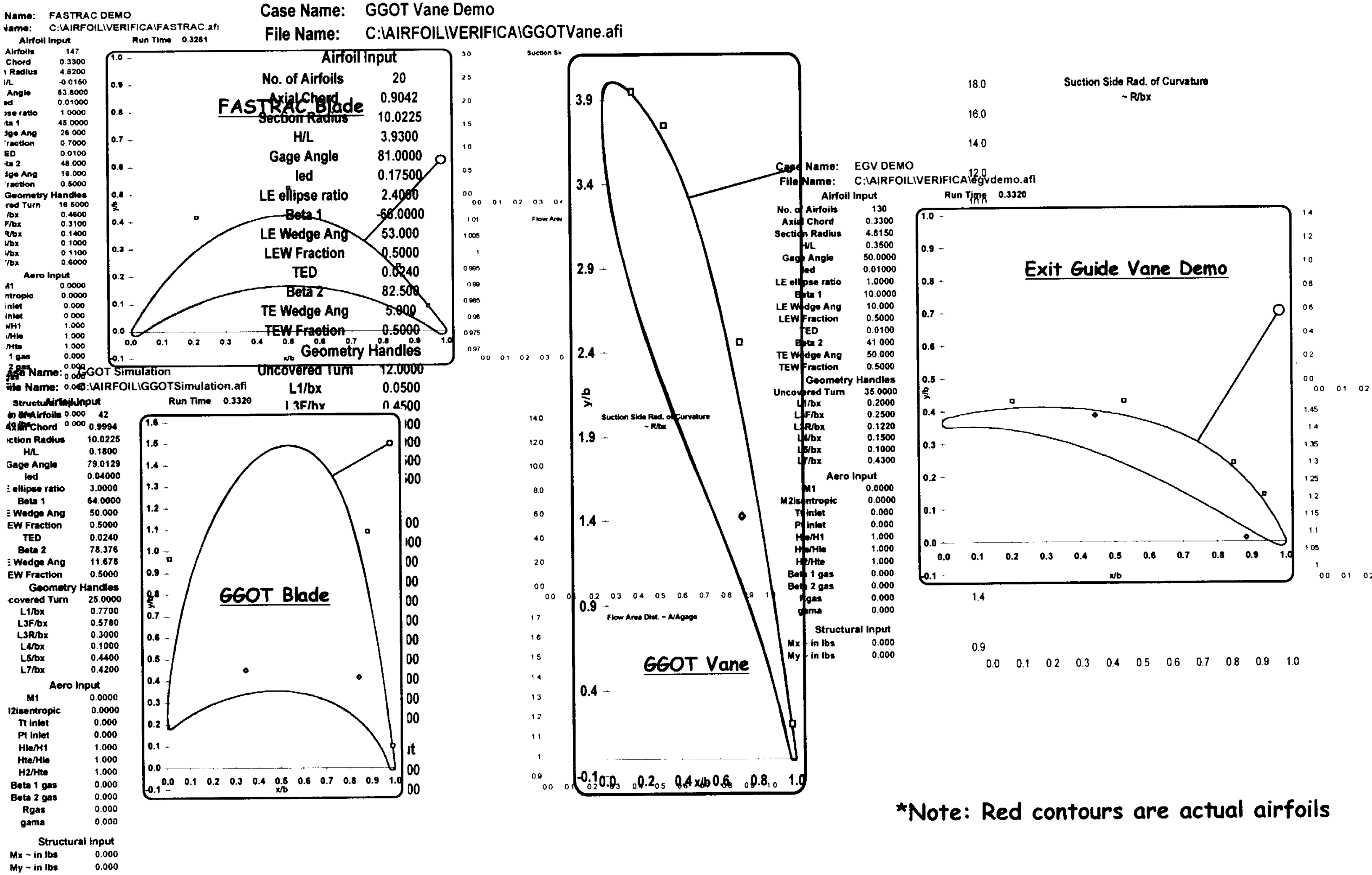
Turbine Aerodynamic Design Tool Development

Wildcat Computed Static Pressure Distribution



Turbine Aerodynamic Design Tool Development

Airfoil Generator Verification ~ Simulation of existing designs*

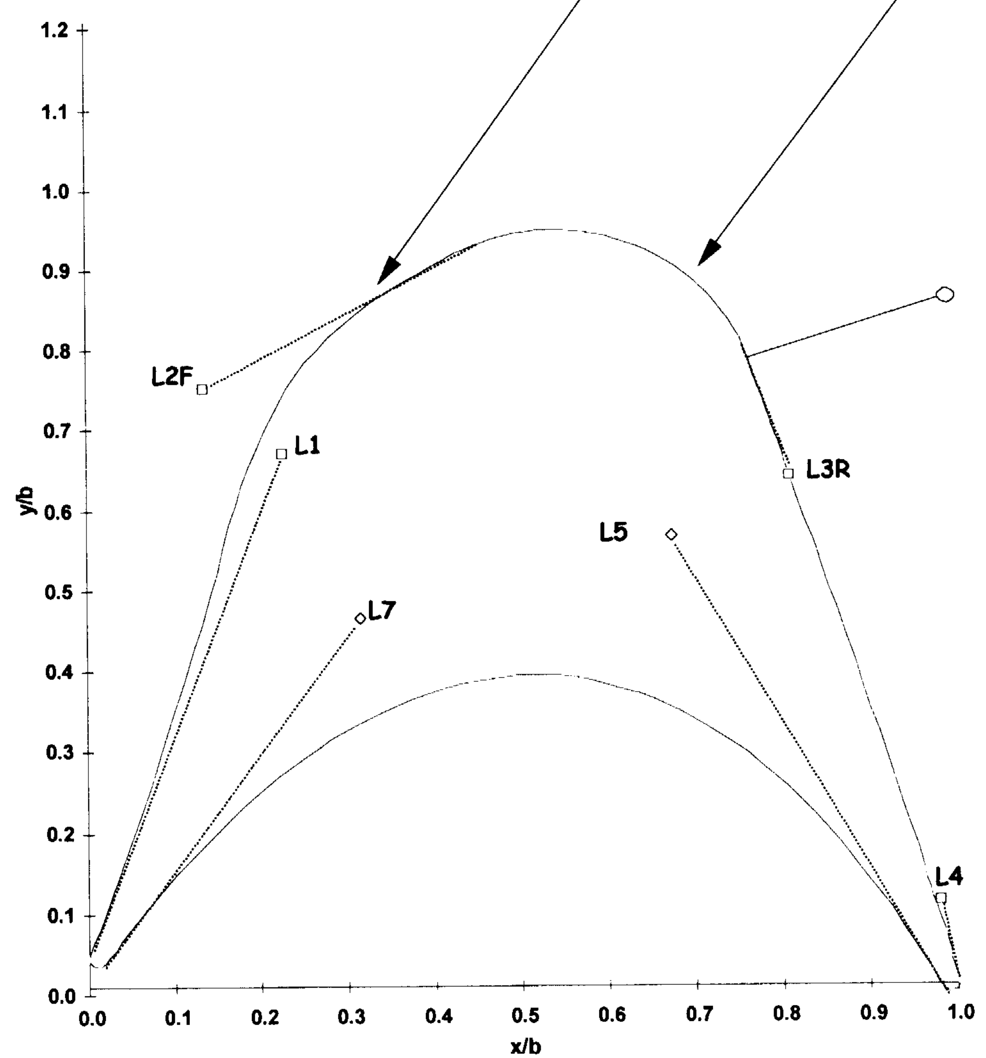


*Note: Red contours are actual airfoils

Turbine Aerodynamic Design Tool Development

Airfoil Generator - Alternate approach for supersonic blading

Mid suction side consists of Bezier curve and circular arc



Turbine Aerodynamic Design Tool Development

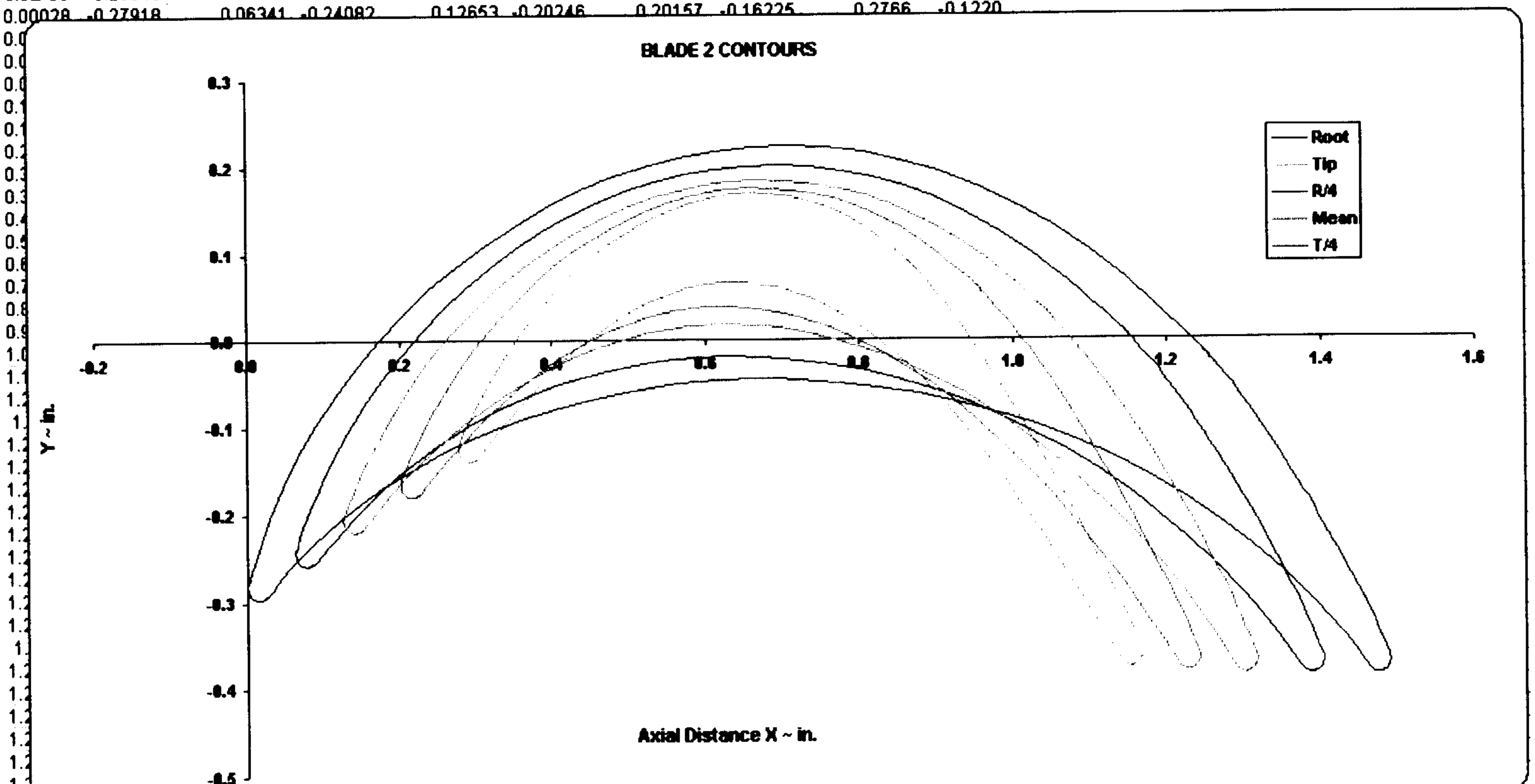
Radial Fairing of Airfoil Contours - 3D CFD Coordinate File Generation

Blade Root		Blade Quarter Root		Blade Mean		Blade Quarter Tip		Blade Tip	
Radius =	4.886	Radius =	5.293	Radius =	5.7	Radius =	6.107	Radius =	6.514
X	Y	X	Y	X	Y	X	Y	X	Y
0	-0.2818	0.0631	-0.24349	0.1262	-0.20517	0.20129	-0.16509	0.27638	-0.1250
8.5E-05	-0.28046	0.0632	-0.24212	0.12631	-0.20378	0.20136	-0.16363	0.27642	-0.1235
0.00028	-0.27918	0.06341	-0.24082	0.12653	-0.20246	0.20157	-0.16225	0.2766	-0.1220
1.27657	-0.04417	1.17244	-0.01796	1.06831	0.00826	0.97325	0.04283	0.87819	0.0774
1.28371	-0.05228	1.18185	-0.02811	1.07999	-0.00394	0.98373	0.03221	0.88748	0.0684

Blade X offset for engine position
5.572

Output Coord File

Output Blade "xyz" File



Turbine Aerodynamic Design Tool Development

Airfoil Contour Generation - Summary

- Codes verified and operational at MSFC
  - Conventional contours
  - Supersonic contours
  - Design Matrix Processing version

Turbine Aerodynamic Design Tool Development

Summary

Turbine Aerodynamic Design System in place and operational at MSFC